LOW COST PAPER-BASED AND INKJET-PRINTED WIRELESS SENSORS

An Undergraduate Research Scholars Thesis

by

JUNGBIN ERIC PARK

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ABSTRACT

Low Cost Paper-based and Inkjet-Printed Wireless Sensors

Jungbin Eric Park
Department of Electrical Engineering
Texas A&M University

Research Advisor: Dr. Jun Kameoka
Department of Electrical Engineering
Texas A&M University

Developing low cost sensor with wireless capability will be researched through exploring different circuit patterns for detecting change, using conductive ink printed as a circuit onto paper substrates, and analyzing which signal emitted by simple antenna. The application of such technology is important in many industries such as agriculture and manufacturing where environmental factors affect the outcome of products. For example, wrong humidity can not only cause decaying in certain food but also render electronic equipment useless. Another use case is disposable biosensors to detect glucose level in blood. Low cost circuits will allow them to be disposed without great penalty increasing safety. Paper-based and inkjet-printed circuits are suitable for such applications due to the low-cost nature and other advantages discussed in the paper. With previous research on Inkjet-printed circuits, wireless biosensors and flat antennas, our research is attempting to combine the technology while reducing the cost and effectivity; expected outcome of the project is mature but low-cost development of cellulose-based senor and close-range antenna on paper to transmit signals depending on what is being measured.

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Finally, I would like to show gratitude to my parents for their support (psychologically and financially) and encouragement throughout the school years.

CHAPTER I

INTRODUCTION

Although other important factors to consider can be accuracy and sensitivity of the sensor andrange of the antenna, low-cost point-of-care devices have begun to be very important for the market; as technology develops and modern innovations in sensor continue to advance, time and cost reduction have become the main focus. To achieve such goals, it requires that there are changes in material, circuitery, and process of manufacturing. With a new focus of cellulose or paper, which have been getting a lot of attention lately due to their positive mechanical properties, using it as a base plate for circuit design is beneficial to keep the design simple and low cost.

Benefits of Paper-based Circuit

Application of the technology date back to paper capacitors and printed circuit boards in the early 20th century [1]. Since then, various sensor designs have been demonstrated. Paper is composed of cellulose networks which makes paper flexible, disposable, light, and low cost. Another beneficial factor is that paper is abundant and available across the world. With such properties, electric devices printed on paper will bring a huge technological impact. According to Henry group in 2012, electrochemical sensing for paper-based mechanism is one of the most common and most effective methods for its accuracy and reliability [2].

Another technology to meet the popular demands of cost saving and time reduction for manufacturing is fabrication of printed circuit boards using printers. This particular method has become popular due to its low-cost equipment, ease of use, and ability to mass produce circuit designs. Specifically, inkjet printing has significant advantages in development of low-cost analytical devices [3]. Inkjet printing is also readily available in home and office environments everywhere and regular printers can be modified to use custom ink for paper-based printed circuit board fabrication [4, 5]. For example, a commercial piezoelectric printer, Fujifilm Dimatix Materials Printer, has been converted successfully to print silver and gold ink patterns on a paper substrate by Maattanen et al. [6]. Finally, the technology also does not require any pre-fabrication; it just needs CAD design fed to the printer to start printing. Combined with the benefits of cellulose, these advantages of inkjet printing will be superior fabrication technique compared to other methods such as screen printing.

Requirements

To meet the requirements of receiving enough electrical power to operate the sensor pattern and send the collected corresponding data back to the origin, the conductivity of the inkjet patterns must be high. To achieve this, material that meet this particular condition while being inexpensive and accessible should be used; we have found that using silver is viable. Techniques such as removing impurities from the metal used and alignment can also provide higher conductivity. We have implemented both methods, but because the printer being used to create inkjet patterns was cheap, there were also some difficulties in patterning the designs for optimal and consistent conductivity.

Because other circuit patterns and components should not affect the results from the sensing sections, most of the circuitry had to be guarded from the environment as well. For example, when humidity can affect other components of the circuit causing inconsistent result. To prevent this, we used polydimethylsiloxane or PDMS layer to shield the system from the environment.

Simulations

Many antenna patterns were tested using Ansys HFSS and ADS antenna simulation throughout the course of the research. The most optimal antenna design for printing in 2-dimensional paper surface was found and tested.

CHAPTER II

METHODS

Antenna Design

After various antenna designs are tested and simulated using the ADS and HFSS, based on the optimal values and the system's use cases, we came up with a design indicated in the figure 1 below. Please note that the figure is not drawn to scale.

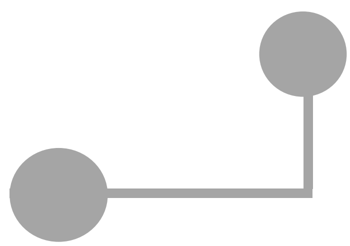

Figure 1. The schematics of the antenna sections

This design, after many tests, was found to be the most optimal design; since the whole system is going to be printed on paper (cellulose-based), the antennas will not have a solid ground or transferring medium. Also, as the incoming and outgoing signals should propagate in the same direction, this 2-dimensional design allows relatively easy printing while satisfying this condition.

One antenna is in charge of receiving the signal from a device and another is in charge of sending the signal back for further data processing. The capacitive sensor unit would be placed in between the two antennas. The figure in the summary section will describe the antenna's role in the whole system in more detail.

To test the actual applications of the system and whether we get a meaningful and quantifiable data from the system, we tested the antenna capabilities and the sensing material's response in different soils with varying humidity.

Printing

There were some difficulties printing with the printer we had access to. First of all, since we were not using official and supported ink (we were printing our own ink best suited for the circuit), there were compatibility issues and scaling issues. After designing what we want to print and saving the file as bmp file, we had to set up the printer in certain ways each time to scale it properly. This meant, whenever we have a new design we want to print, we had to adjust the printer each and every time using trial and error.

Also, because the printer deposits ink in a linear fashion and the refresh rate was not as high as what we wanted it to be, there were many cases where to circuit had very high resistivity in areas that were printed in different direction than how the ink head moves. For instance, when the printer ink head moves horizontally but prints a vertical design, the resistivity in that area would be relatively high rendering the circuit useless. The solution to this problem is getting a higher quality printer or pausing and physically rotating the circuit being printed (latter method is what we chose to do).

Surface PDMS Coating

Since paper/cellulose is a substance which is fragile and sensitive to certain properties of the environment, we coated the surface of the circuit with PDMS to prevent any damages to the paper, thereby changing resistivity and other qualities which might affect the sensor output; for example, in humid environments, the entire system might render useless once the cellulose is exposed. We excluded the sensing part of the circuit from coating to prevent PDMS from blocking what we are trying to sense with the circuit.

Summary

In summary, we transmit an electromagnetic signal to one of the antenna portion of circuit for delivering enough electrical power. Then, a capacitive sensor will sense relevant data such as humidity, temperature, etc. from the environment; this is done by a capacitive change in the circuit. Finally, the lower antenna will reflect electrical signals back to us for signal analysis. Lower figure shows the whole process visually.

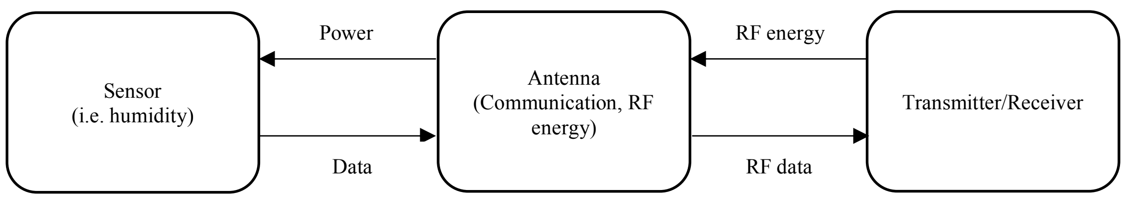

Figure 2: Flowchart of the system

CHAPTER III

RESULTS

An anticipated result of the integrated system was a signal change (possibly decrease in the strength and frequency response) depending on the environment and its different conditions such as humidity, etc. However, due to the unforeseen events surrounding the COVID-19 virus in spring 2020, complete data was unavailable at the time of publication for this URS thesis. This means that, at the current state, we only have insignificant and insufficient data of the whole system. As the research labs are all closed and the research progress is on hold, it seems very difficult to continue the research for around 3 to 4 months. Acquiring the result will continue after 3 months and will be added.

Speculations and expected outcomes are discussed in the conclusion.

CHAPTER IV

CONCLUSION

The benefits of cellulose and inkjet printing showed that this particular fabrication method has a lot of potentials such as it being inexpensive and easily accessible. With these benefits in mind, we came up with a sensor integrated with antennas. The design allowed a system to be wireless, meaning it does not have to be connected to an electrical source to function, and easily printed and placed; the design was executed to take advantage of the benefits. However, due to the unforeseen events surrounding the COVID-19 virus in spring 2020, complete data was unavailable at the time of publication for this URS thesis. Further data processing will be done after 3 to 4 months.

From the current status of the progress, there needs to be multiple improvements in printing the circuit pattern for less resistivity, simulations and tests of different 2-dimensional antenna patterns, and examination of the system in the real-world environments. There had been discussions of acquiring a new inkjet printer due to the issues mentioned above in the methods sections. Also, we are looking into other pure metals to check if it could improve the overall resistivity.

Based on the movement of the research and other research on battery-less wireless sensors, the integrated system seems more than possible; there has been successful cases of various types of cellulose based sensors in manufacturing/farming applications and wireless circuitry with wired power source. By thorough continuing the research in the steps mentioned above, the team suspects the project will have a solid outcome; a paper-based inkjet-printed circuit that is powered by an electromagnetic wave and able to transmit applicable data back for analysis.

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